A SINGLE CRYSTAL SiC PLUG-AND-PLAY HIGH TEMPERATURE DRAG FORCE TRANSDUCER

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ABSTRACT

A novel fully packaged single crystal piezoresistive 6H-silicon carbide (6H-SiC) drag force transducer based on cantilever beam deflection was demonstrated for the first time in a hot (~600 °C) section of a gas turbine engine to study turbulence. The beam deflection was directly proportional to the force induced by the flow stream. The induced strain was transferred to the piezoresistors that were etched into the 6H-SiC epilayer and arranged in a Wheatstone bridge circuit configuration. The transducer measured natural frequency of 35 kHz was in good agreement with the calculated value of 35.76 kHz. The presumed turbulence was extracted by subtracting the ensemble mean waveform signal and averaging the results. The post engine test at lower temperature and up to Mach 0.8 indicated the typical second order, v^2, response of anemometers, where v is the average flow velocity. This result confirmed that the transducer survived the high temperature test. The result provided further confirmation of the potential application of semiconductor SiC as a piezoresistive sensor operating at temperatures that are beyond the functional capability of conventional silicon based sensors.

INTRODUCTION

There is a technology evolution toward the rapid development of new generation turbine engines based on modeling of engine behavioral parameters leading to a computerized production process. There is also the need for comprehensive round-the-clock health monitoring of engine performance for the purpose of increasing aviation safety, efficient energy management, and improved control of NOx and hydrocarbon emissions [1]. To meet these needs, modeling and simulations are performed using codes that are generated by Computational Fluid Dynamics (CFD). Results obtained from these codes largely form the basis on which decisions that determine changes in the engine are made. It is therefore crucial that these codes be very accurate in predicting the behavior of the engine. Validation of the accuracy of these CFD codes require the direct measurement of critical behavioral parameters such as pressure, flow, and temperature, the results of which are compared against the ones from CFD calculations. Utilizing direct measurement will enable further improvement of the CFD codes, thereby minimizing errors in simulations and increasing the confidence of using the codes.

The use of a silicon based drag force anemometer to measure turbulence was previously demonstrated [2], but was limited to low temperature (<200 °C). In cases where the measurement exceeded this temperature, the results were largely unreliable due to limitations imposed by the sensor and package material properties. Since the silicon sensor and packaging components were made from different materials, the mismatch created by differences in their coefficients of thermal expansion (CTE) caused undesirable transient thermomechanical stresses to be induced on the sensor. The typical outcome of this effect was creep and fatigue that usually resulted in gradual deviation from accurate measurement and eventual failure. Also, the packaging methods adopted did not allow for the required precision placement of the cantilever beam sensor. As a result, it was usually misaligned, leading to the generation of undesirable shear stresses when inserted in the flow field. Also, maximum strain was not transferred to the piezoresistive strain gauges because of the imprecise placement of the cantilever beam sensor on the clamped edge. The inconsistent placement of the cantilever beam also meant that measurements from one sensor to another would vary. The conventional silicon based drag force sensor utilized wirebonding technology, which was usually not reliable in the high temperature and extreme vibration environments that are typical of these engines. Furthermore, the bond wires were suspected of acting as antennas that received spurious electromagnetic noises generated in the environment. These noise signals interacted with actual signals and disturb the latter.

Due to the excellent thermomechanical properties of SiC and its fairly high gauge factor [3], sensors made from the material can be inserted into higher temperature (>300 °C) environments than is currently possible with silicon based sensors. As a result, turbulence measurements can be performed at higher temperatures, thereby making possible accurate validation of CFD codes in that temperature regime. In this paper, we report the first demonstration of the use of a prototype miniature 6H-SiC drag force transducer in a high temperature (~600 °C) section of a turbine engine. Two novel processes were introduced during the implementation of the transducer. First, the packaging components were fabricated out of polycrystalline silicon carbide (polySiC) substrates that were grown by chemical vapor deposition (CVD) [4]. They were fabricated into semi-encapsulating sandwich components to match the CTE of the 6H-SiC cantilever beam. This eliminated creep and fatigue as potential failure mechanisms as well as the errors associated with such mismatch. Second, electrical connection was made by compression bonding method, thereby eliminating the problems associated with wire bonding during operation in high temperature and high vibration environments.

FABRICATION AND ASSEMBLY

The fabrication of the 6H-SiC drag force transducer can be divided into two segments: Batch fabrication of the piezoresistors in single crystal n-type 6H-SiC epilayer and the batch fabrication of the 500 µm thick CVD-polySiC substrates. The 2 µm thick single crystal 6H-SiC n-type epilayer was homoepitaxially grown on a 300 µm thick high resistivity (8 Ω-cm) p-type 6H-SiC wafer by a CVD process [5], thereby forming an n-p junction. To fabricate the resistors, a 200 nm thick nickel etch mask was sputter-deposited on to photoresist, in which resistor patterns were previously defined by conventional photolithographic process. This was followed by a lift-off process that left the resistor patterns in the nickel etch mask. Etching of the piezoresistors in the n-type epilayer was performed by conventional plasma etching using a NF_3/Ar gas mixture. After stripping the Ni etch mask in equal volumes of nitric and hydrochloric acids, the wafer was thermally oxidized to passivate the piezoresistors and the exposed sections of the p-type wafer. Contact vias were etched in the oxide by conventional wet etching in buffered hydrofluoric acid. Subsequently, ohmic contact multilayer metallization of Ti/$TaSi_2$/Pt was sputter-deposited, patterned, and annealed. The ohmic contact scheme was previously demonstrated to be thermally stable at 600 ^oC in air for over 1000 hours [6]. The wafer was then diced into individual cantilever beam sensors as shown in Fig. 1a, with the corresponding electrical circuit diagram also shown. The Figure also shows the plasma etched piezoresistors in the n-type 6H-SiC epilayer and the exposed sections of the p-type SiC wafer. Also shown are five bondpads of the patterned thermally stable high temperature metallization. The piezoresistors were arranged in a Wheatstone bridge circuit configuration such that they were alternately placed along the longitudinal (R_{l1} and R_{l2}) and transverse (R_{t1} and R_{t2}) directions. The four resistors were designed to have the same resistance value.

The transconnect metallization provided electrical connection between the sensor bondpads and the plug-and-play-pins. The polySiC substrate on which the transconnect metallization was to be patterned was initially thermally oxidized at 1150 ^oC for 12 hours to obtain oxide thickness of 200 nm, followed by the sequential deposition of titanium (100 nm), platinum (300 nm), and aluminum (1 µm). Photoresist was then applied and the transconnect pattern defined in it. Trimethylaluminum hydroxide was used to develop the photoresist, which also etched the aluminum layer. The patterned aluminum was thus used as an etch mask during the reactive ion etching of the platinum and titanium in argon plasma. The patterned transconnect metallization is shown in Figure 1b.

The trenches and cavities in the second polySiC substrate functioned to accept the plug-and-play pins and the 6H-SiC piezoresistive sensors, respectively. The batch etching of the array of trenches and cavities was accomplished by the deep reactive ion etching [7] of the polySiC. The etched depth of the trenches and cavities was intentionally made to be approximately 288 µm, which was 2 µm less than the thickness of the p-type SiC wafer. Thus, when the plug-in pins and the cantilever beam were inserted into the trenches and the cavity, respectively, they were approximately 2 µm microns above the planar surface of the polySiC. A 12-hour blanket thermal oxidation at 1150 ^oC of the polySiC was performed prior to inserting the pins and the cantilever beam. It dielectrically isolated the trenches from each other, thereby preventing leakage current between the pins through the substrate. After batch fabrication, the two polySiC substrates were diced into individual cells as shown in Figs. 1b and c. In Fig. 1c, the cantilever was slid all the way into the cavity of the polySiC and held down with a high temperature glass frit that was fired in nitrogen ambient at 600 ^oC for fifteen minutes. The cavity dimension was micromachined to accommodate the dimension of the cantilever beam so that the cantilever beam section consisting of the bondpads, the transverse piezoresistors, and a small segment of the longitudinal piezoresistors rested on its base. The other section of the cantilever beam that included the longer segment of the longitudinal piezoresistors and the p-type wafer can be seen to overhang the clamped edge of the cavity. Thus, when the free standing section of the cantilever beam was pushed down, the bending would induce maximum strain at the clamped edge. The maximum strain is transferred only to the longitudinal piezoresistors while the transverse piezoresistors remained unstrained. The plug-and-play pins were then inserted into the trenches. The diameter of the pins was the same as the width of the trench but a few microns above the planar surface of the polySiC substrate. Next, the polySiC with the patterned transconnect metallization was flipped and brought in intimate contact with the polySiC containing the trenches and cavity. Each set of transconnects had five strips that started from one end as narrow strips, then widened equidistantly as they extended to the other end. The wider section of the transconnect self-aligned with the pins and made intimate contact. The narrow section of the transconnect self-aligned

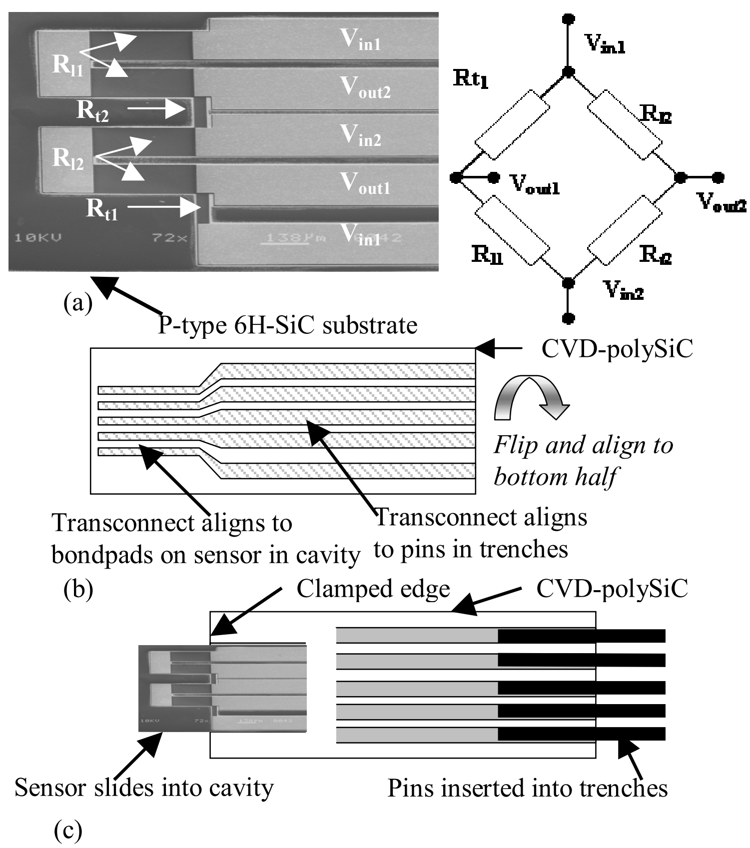
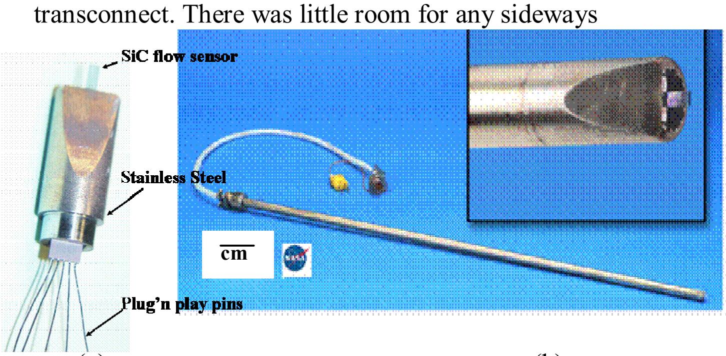


Figure 1: Components of the high temperature drag force transducer showing **a)** the 6H-SiC cantilever beam sensor, **b)** the transconnect metallization on oxidized polySiC and **c)** the pins and sensor inserted into the etched and oxidized trenches and cavity, respectively.

simultaneously with the five bondpads on the 6H-SiC cantilever beam and also made intimate contact. As a result of the precision etching adopted, misalignment was insignificant since a deliberate width offset compensation of the bondpads and transconnect was designed into the masks used. When the polySiC sandwich pair was tightly compressed, the transconnect made permanent contact with the cantilever beam at one end and the plug-in pins at the other. Only the freestanding end of the sensor was not encapsulated.

Compression was made possible by inserting the polySiC pair into the pre-fabricated stainless steel housing shown in Fig. 2a. The stainless steel housing had two screws, each dedicated to clamp on the narrow and wider section of the transconnect. There was little room for any sideways



(a) (b)

Figure 2: **a)** Plug-and-play 6H-SiC drag force transducer; **b)** transducer plugged (inset) into a long probe for easy and direct insertion into the hot engine section.

movement of the polySiC sandwich pair in the stainless steel housing because of the tight tolerance imposed. The transducer now became a standalone plug-and-play product, as shown in Fig. 2a. A prototype was plugged into a five-pin horizontal socket at the end of a long probe as shown in Fig. 2b, thus allowing the insertion of the transducer deep into the engine. The unclamped section of the cantilever was the only part exposed in the flow field.

EXPERIMENT AND RESULTS

The objectives of the initial experiment were to validate the survivability of the drag force sensor and its ability to measure turbulence by direct insertion into the flow field at the final stage of the turbine engine where the temperature was as high as 600 °C. The transducer was inserted inside the engine so that the broad face of the cantilever beam was perpendicular to the flow stream. The induced maximum strain at the clamped edged was transferred to the longitudinal piezoresistors sitting on the beam. The natural frequency of the transducer was calculated with the equation:

$$f_n = 0.1615 \frac{t}{L^2} \sqrt{\frac{E}{\rho_b}} \qquad (1)$$

where L was the freestanding length of the cantilever beam (4 mm), t was the thickness (0.3 mm), ρ_b the density of 6H-SiC (3211 kg-m^{-3}) and E the Young's modulus (448 GPa). The transducer was initially tested in a low temperature flow field with a frequency spectrum analyzer connected to it. Fig. 3 shows the measured frequency response of the sensor, which indicated a resonance frequency of 35 kHz, in good agreement with the calculated value of 35.76 kHz. The error was likely due to material parameteric approximations.

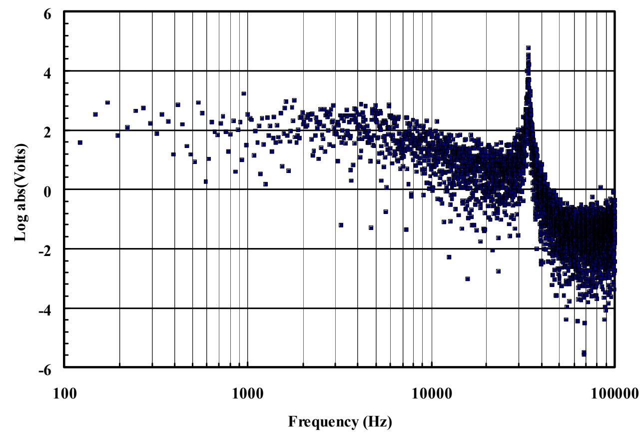


Figure 3: The resonance frequency of the 6H-SiC drag force transducer was in good agreement with calculated value of 35.76 kHz.

The maximum induced strain on the cantilever beam at the clamped edge, is generally expressed as:

$$\varepsilon = 6M\left(Ewt^2\right)^{-1} \qquad (2a)$$

where ε is the induced strain, w is the width (1.75 mm) and M is the bending moment (N-m) of the beam, which in this case was expressed in terms of the drag force, D [8], as:

$$M = DL = \left(C_D \frac{\rho_f U^2}{2g_c} wL\right)L \qquad (2b)$$

where C_D is the drag coefficient and U is the mean flow velocity of the gas stream (m-s^{-1}), and ρ_f is the fluid density (g-cm^{-3}). The gravity conversion factor, g_c, in this case was 1. The induced strain as expressed in Equation (2a) was coupled to the longitudinal piezoresistive coefficient, π (cm^2/dyne), and the relative change in bridge voltage of the SiC and expressed as:

$$\frac{\Delta V}{V_{in}\varepsilon} = \pi(T, N)E \qquad (3)$$

where ΔV (V), and V_{in} (V) is the change in Wheatstone bridge output voltage when the beam was strained and the input voltage, respectively. The product term on the right hand side is essentially the gauge factor of the 6H-SiC piezoresistor, which is a function of doping (N) and temperature (T). Thus, by substituting for strain from Equation (2a) and moment from (2b) into (3), a complete coupling of the mean flow velocity, strain and electrical response was obtained and expressed as:

$$\Delta V = V_{in} \frac{3C_D \pi(T, N)\rho_f U^2 L^2}{t^2} \qquad (4)$$

From Equation (4), it can be seen that the bridge output of the transducer is proportional to the square of the mean flow velocity of the gas stream, thereby allowing for the extraction of the mean flow velocity once the output voltage was known.

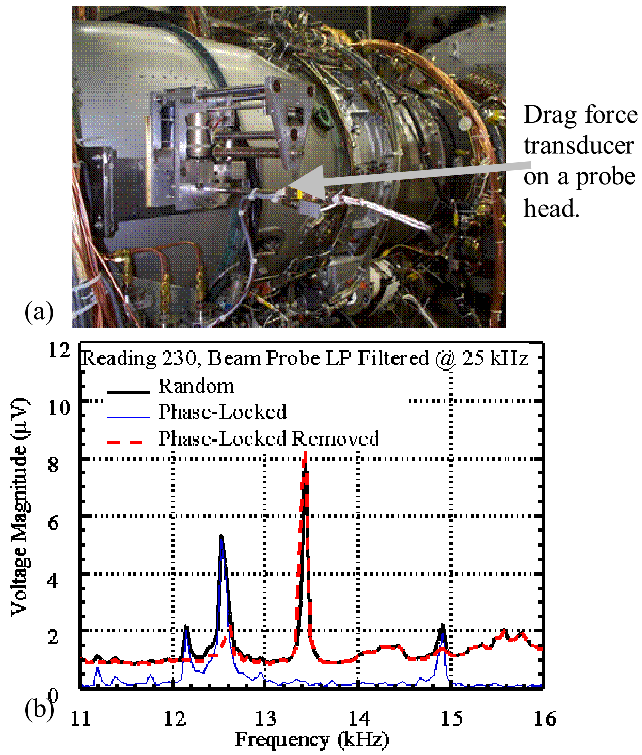


Figure 4: **a)** The 6H-SiC drag force transducer plugged into a probe head and inserted into the engine; **b)** Spectra of the total signal, the periodic unsteadiness (phase-locked), and the difference (phase-lock removed), presumed to be the turbulence.

To validate the ability to measure flow velocity in a real environment, a prototype of the transducer was inserted into the final stage of a Pratt & Whitney 545 turbine engine as shown in Fig. 4a. The temperature at this last stage is about 600 ^{o}C. The unsteady signal consisted of a mean value component, a periodic unsteady component, and a random unsteady component. The periodic unsteadiness was presumed to arise from blade wakes, etc., and the random unsteadiness was presumed to arise from turbulence. To isolate the turbulence, the periodic unsteadiness must be removed from the total signal. Figure 4b shows the spectra of the total random signal and the signal of the phase-locked periodic unsteadiness. The spectrum of the difference, shown with the phase-locked removed, was presumably the turbulence. The low bridge output voltage was the combined effect of the drop in strain sensitivity (not of the beam) of the piezoresistors with increasing temperature (see Equation 4) and the absence of signal amplification during the test. The survivability of the transducer was further verified during the post engine test at lower temperature by conducting another frequency response analysis, which showed no deviation in the resonance frequency from the pre engine test value of 35 kHz..

CONCLUSION

Since the objectives of initial experiment were to validate the survivability of the transducer and its ability to measure flow in high temperature, the complexities associated with the data collection and the proper interpretation of the presumed turbulence is still subject to further analysis and understanding. Most importantly, in this work, we have for the first time demonstrated the operation of a prototype 6H-SiC drag force transducer to measure flow velocity in a turbine engine section where the temperature was about 600 ^{o}C. The transducer's sensitivity to temperature, which is typical of semiconductor piezoresistive sensors, implies that future generation transducers will need either on-chip or external temperature compensation. This work has significant impact on next generation aero and space vehicles, which will require active control systems for round-the-clock health monitoring of engine performance to increase safety, achieve efficient energy management, and improved control of undesirable emission of noise, NOx and hydrocarbons. The future improvement of the transducer's functional characteristics will provide a new generation of robust tools for high temperature instrumentation that can operate reliably beyond the capability of conventional semiconductor sensors. It also opens new technology opportunities for the eventual integration of other SiC sensors such as temperature sensors, pressure sensors, and high temperature control electronics. An integrated system will allow the use of a single probe to simultaneously measure the above three parameters required for total flow characterization.

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